

5.1 Petroleum Refining¹

5.1.1 General Description

The petroleum refining industry converts crude oil into more than 2500 refined products, including liquefied petroleum gas, gasoline, kerosene, aviation fuel, diesel fuel, fuel oils, lubricating oils, and feedstocks for the petrochemical industry. Petroleum refinery activities start with receipt of crude for storage at the refinery, include all petroleum handling and refining operations, and ~~they~~ terminate with storage preparatory to shipping the refined products from the refinery.

The petroleum refining industry employs a wide variety of processes. A refinery's processing flow scheme is largely determined by the composition of the crude oil feedstock and the chosen slate of petroleum products. The example refinery flow scheme presented in Figure 5.1-1 shows the general processing arrangement used by refineries in the United States for major refinery processes. The arrangement of these processes will vary among refineries, and few, if any, employ all of these processes. Petroleum refining processes having direct emission sources are presented on the figure in bold-line boxes.

Listed below are 5 categories of general refinery processes and associated operations:

1. Separation processes
 - a. Atmospheric distillation
 - b. Vacuum distillation
 - c. Light ends recovery (gas processing)
2. Petroleum conversion processes
 - a. Cracking (thermal and catalytic)
 - b. Reforming
 - c. Alkylation
 - d. Polymerization
 - e. Isomerization
 - f. Coking
 - g. Visbreaking
3. Petroleum treating processes
 - a. Hydrodesulfurization
 - b. Hydrotreating
 - c. Chemical sweetening
 - d. Acid gas removal
 - e. Deasphalting
4. Feedstock and product handling
 - a. Storage
 - b. Blending
 - c. Loading
 - d. Unloading
5. Auxiliary facilities
 - a. Boilers
 - b. Waste water treatment
 - c. Hydrogen production
 - d. Sulfur recovery plant

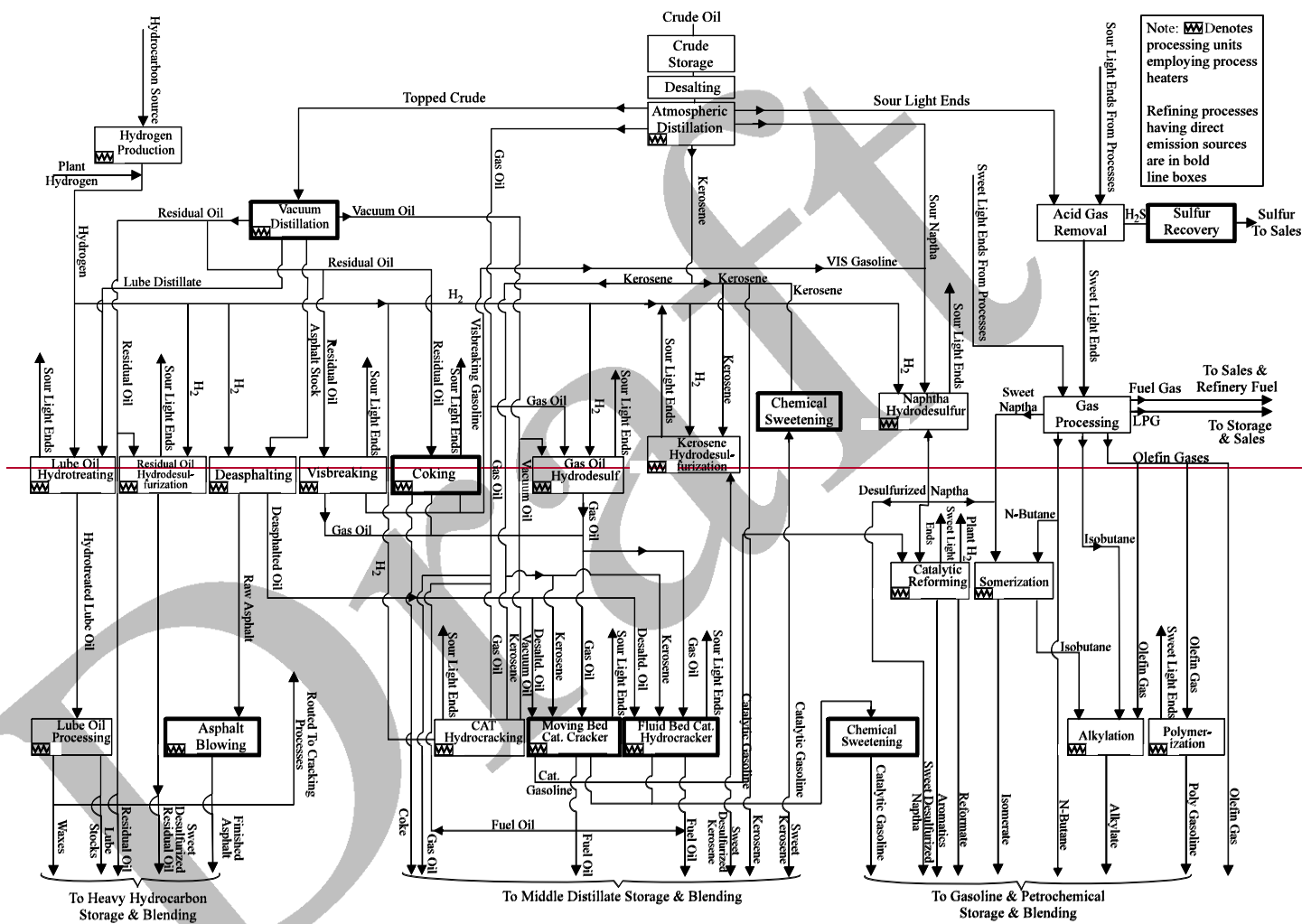


Figure 5.1-1. Schematic of integrated petroleum refinery.

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- e. Cooling towers
- f. Blowdown system
- g. Compressor engines

These refinery processes are defined below, and their emission characteristics and applicable emission control technology are discussed.

5.1.1.1 Separation Processes -

The first phase in petroleum refining operations is the separation of crude oil into its major constituents using 3 petroleum separation processes: atmospheric distillation, vacuum distillation, and light ends recovery (gas processing). Crude oil consists of a mixture of hydrocarbon compounds including paraffinic, naphthenic, and aromatic hydrocarbons with small amounts of impurities including sulfur, nitrogen, oxygen, and metals. Refinery separation processes separate these crude oil constituents into common boiling-point fractions.

5.1.1.2 Conversion Processes -

To meet the demands for high-octane gasoline, jet fuel, and diesel fuel, components such as residual oils, fuel oils, and light ends are converted to gasolines and other light fractions. Cracking, coking, and visbreaking processes are used to break large petroleum molecules into smaller ones. Polymerization and alkylation processes are used to combine small petroleum molecules into larger ones. Isomerization and reforming processes are applied to rearrange the structure of petroleum molecules to produce higher-value molecules of a similar molecular size.

5.1.1.3 Treating Processes -

Petroleum treating processes stabilize and upgrade petroleum products by separating them from less desirable products and by removing objectionable elements. Undesirable elements such as sulfur, nitrogen, and oxygen are removed by hydrosulfurization, hydrotreating, chemical sweetening, and acid gas removal. Treating processes, employed primarily for the separation of petroleum products, include such processes as deasphalting. Desalting is used to remove salt, minerals, grit, and water from crude oil feedstocks before refining. Asphalt blowing is used for polymerizing and stabilizing asphalt to improve its weathering characteristics.

5.1.1.4 Feedstock And Product Handling -

The refinery feedstock and product handling operations consist of unloading, storage, blending, and loading activities.

5.1.1.5 Auxiliary Facilities -

A wide assortment of processes and equipment not directly involved in the refining of crude oil is used in functions vital to the operation of the refinery. Examples are boilers, waste water treatment facilities, hydrogen plants, cooling towers, and sulfur recovery units. Products from auxiliary facilities (clean water, steam, and process heat) are required by most process units throughout the refinery.

5.1.2 Process Emission Sources And Control Technology

This section presents descriptions of those refining processes that are significant air pollutant contributors. Process flow schemes, emission characteristics, and emission control technology are discussed for each process. Table 5.1-1 lists and 5.1-2 list the emission factors for direct-process emissions in petroleum refineries. Factors are expressed in units of kilograms per 1000 liters (kg/10³ L) or

Table 5.1-1 (Metric And English Units). EMISSIONS FACTORS FOR PETROLEUM REFINERIES ^a

Process	Particulate	Sulfur Oxides (as SO ₂)	Carbon Monoxide	Total Hydro- carbons ^b	Nitrogen Oxides (as NO ₂)	Aldehydes	Ammonia	EMISSION FACTOR RATING
Boilers and process heaters								
Fuel oil				See Section 1.3 - "Fuel Oil Combustion"				
Natural gas				See Section 1.4 - "Natural Gas Combustion"				
Fluid catalytic cracking units (FCC) ^c								
Uncontrolled								
kg/10 ³ L fresh feed	0.695 (0.267 to 0.976)	1.413 (0.286 to 1.505)	39.2	0.630	0.204 (0.107 to 0.416)	0.054	0.155	B
lb/10 ³ bbl fresh feed	242 (93 to 340)	493 (100 to 525)	13,700	220	71.0 (37.1 to 145.0)	19	54	B
Electrostatic precipitator and CO boiler								
kg/10 ³ L fresh feed	0.128 ^d (0.020 to 0.428)	1.413 (0.286 to 1.505)	Neg	Neg	0.204 ^e (0.107 to 0.416)	Neg	Neg	B
lb/10 ³ bbl fresh feed	45 ^d (7 to 150)	493 (100 to 525)	Neg	Neg	71.0 ^e (37.1 to 145.0)	Neg	Neg	B
Moving-bed catalytic cracking units ^f								
kg/10 ³ L fresh feed	0.049	0.171	10.8	0.250	0.014	0.034	0.017	B
lb/10 ³ bbl fresh feed	17	60	3,800	87	5	12	6	B
Fluid coking units ^g								
Uncontrolled								
kg/10 ³ L fresh feed	1.50	ND	ND	ND	ND	ND	ND	C
lb/10 ³ bbl fresh feed	523	ND	ND	ND	ND	ND	ND	C
Electrostatic precipitator and CO boiler								
kg/10 ³ L fresh feed	0.0196	ND	Neg	Neg	ND	Neg	Neg	C
lb/10 ³ bbl fresh feed	6.85	ND	Neg	Neg	ND	Neg	Neg	C

Table 5.1-1 (cont.).

Process	Particulate	Sulfur Oxides (as SO ₂)	Carbon Monoxide	Total Hydro- carbons ^b	Nitrogen Oxides (as NO ₂)	Aldehydes	Ammonia	EMISSION FACTOR RATING
Delayed coking units	ND	ND	ND	ND ^h	ND	ND	ND	NA
Compressor engines ^h								
Reciprocating engines								
kg/10 ³ m ³ gas burned	Neg	2s ^j	7.02	21.8	55.4	1.61	3.2	B
lb/10 ³ ft ³ gas burned	Neg	2s	0.43	1.4	3.4	0.1	0.2	B
Gas turbines								
kg/10 ³ m ³ gas burned	Neg	2s	1.94	0.28	4.7	ND	ND	B
lb/10 ³ ft ³ gas burned	Neg	2s	0.12	0.02	0.3	ND	ND	B
Blowdown systems ^k								
Uncontrolled								
kg/10 ³ L refinery feed	Neg	Neg	Neg	1,662	Neg	Neg	Neg	C
lb/10 ³ bbl refinery feed	Neg	Neg	Neg	580	Neg	Neg	Neg	C
Vapor recovery system and flaring								
kg/10 ³ L refinery feed	Neg	0.077	0.012	0.002	0.054	Neg	Neg	C
lb/10 ³ bbl refinery feed	Neg	26.9	4.3	0.8	18.9	Neg	Neg	C
Vacuum distillation column condensers ^m								
Uncontrolled								
kg/10 ³ L vacuum feed	Neg	Neg	Neg	0.14 (0 to 0.37)	Neg	Neg	Neg	C
lb/10 ³ bbl vacuum feed	Neg	Neg	Neg	50 (0 to 130)	Neg	Neg	Neg	C
Controlled (vented to heater or incinerator)	Neg	Neg	Neg	Neg	Neg	Neg	Neg	C

Table 5.1-1 (cont.).

Process	Particulate	Sulfur Oxides (as SO ₂)	Carbon Monoxide	Total Hydro- carbons ^b	Nitrogen Oxides (as NO ₂)	Aldehydes	Ammonia	EMISSION FACTOR RATING
Claus plant and tail gas treatment				See Section 8.13 - "Sulfur Recovery"				

^a Numbers in parentheses indicate range of values observed. Neg = negligible. ND = no data.

^b Overall, less than 1 weight % of total hydrocarbon emissions is methane.

^c References 2-8.

^d Under the New Source Performance Standards, controlled FCC regenerators must have particulate emissions lower than 0.054 kg/10³ L (19 lb/10³ bbl) fresh feed.

^e May be higher, from the combustion of ammonia.

^{ef} Reference 2.

^g Reference 5.

^h References 9-10.

^j Based on 100% combustion of sulfur to SO₂. s = refinery gas sulfur content (in kg/1000 m³ or lb/1000 ft³, depending on desired units for emission factor).

^k References 2,11.

^m References 2,12-13. If refinery feed rate is known, rather than vacuum feed rate, assume vacuum feed is 36% of refinery feed. Refinery feed rate is defined as the crude oil feed rate to the atmospheric distillation column.

ⁿ Methods for estimating hydrocarbon emissions from decoking operations are presented in Reference 18.

Table 5.1-2 (Metric And English Units). ADDITIONAL EMISSIONS FACTORS FOR FCCU, CRU, AND HYDROGEN PLANTS

<u>SCC</u>	<u>SCC Description</u>	<u>Pollutant</u>	<u>Emissions Factor</u>		<u>Emissions Factor Representativeness</u>
<u>30600201;</u> <u>30600212</u>	<u>Fluid Catalytic Cracking Unit (FCCU)</u> <u>complete burn – with or without CO</u> <u>boiler –controlled ^a</u>	<u>Hydrogen Cyanide</u> <u>(HCN) ^b</u>	<u>0.023 kg/ 10³ L feed</u>	<u>8.0 lb/10³ bbl feed</u>	<u>Moderately</u>
<u>30601602</u>	<u>Catalytic Reforming Unit (CRU) –</u> <u>controlled ^c</u>	<u>Total Hydrocarbons</u> <u>(THC) ^d</u>	<u>0.0011 kg/ 10³ L feed</u>	<u>0.40 lb/10³ bbl feed</u>	<u>Poorly</u>
<u>30601801</u>	<u>Hydrogen Plants - uncontrolled</u>	<u>NOx ^e</u>		<u>0.081 lb/MMBtu</u>	<u>Moderately</u>

^a Applies to controlled units. Factor developed based on units with scrubber or electrostatic precipitator control.

^b References 19-27.

^c Applies to controlled units. Factor developed based on units with chlorosorb or scrubber control.

^d References 28-31.

^e References 32-37.

~~Factors are expressed in units of kilograms per 1000 liters (kg/10³ L) or kilograms per 1000 cubic meters (kg/10³ m³) and pounds per 1000 barrels (lb/10³ bbl) or pounds per 1000 cubic feet (lb/10³ ft³).~~ with the exception of Hydrogen Plants. The factor for Hydrogen Plants is expressed in units of pounds per million British thermal unit heat input (lb/MMBtu). The following process emission sources are discussed here:

1. Vacuum distillation
2. Catalytic cracking
3. Thermal cracking processes
4. Utility boilers
5. Catalytic reforming ~~Heaters~~
6. Hydrogen Production ~~Compressor engines~~
7. Sulfur recovery
8. Blowdown systems
9. Heaters
10. Compressor engines — 8. Sulfur recovery
-
11. Sweetening
12. Asphalt Blowing

5.1.2.1 Vacuum Distillation -

Topped crude withdrawn from the bottom of the atmospheric distillation column is composed of high boiling-point hydrocarbons. When distilled at atmospheric pressures, the crude oil decomposes and polymerizes and will foul equipment. To separate topped crude into components, it must be distilled in a vacuum column at a very low pressure and in a steam atmosphere.

In the vacuum distillation unit, topped crude is heated with a process heater to temperatures ranging from 370 to 425°C (700 to 800°F). The heated topped crude is flashed into a multitray vacuum distillation column operating at absolute pressures ranging from 350 to 1400 kilograms per square meter (kg/m²) (0.5 to 2 pounds per square inch absolute [psia]). In the vacuum column, the topped crude is separated into common boiling-point fractions by vaporization and condensation. Stripping steam is normally injected into the bottom of the vacuum distillation column to assist the separation by lowering the effective partial pressures of the components. Standard petroleum fractions withdrawn from the vacuum distillation column include lube distillates, vacuum oil, asphalt stocks, and residual oils. The vacuum in the vacuum distillation column is usually maintained by the use of steam ejectors but may be maintained by the use of vacuum pumps.

The major sources of atmospheric emissions from the vacuum distillation column are associated with the steam ejectors or vacuum pumps. A major portion of the vapors withdrawn from the column by the ejectors or pumps is recovered in condensers. Historically, the noncondensable portion of the vapors has been vented to the atmosphere from the condensers. There are approximately 0.14 kg of noncondensable hydrocarbons per m³ (50 lb/10³ bbl) of topped crude processed in the vacuum distillation column.^{2,12-13} A second source of atmospheric emissions from vacuum distillation columns is combustion products from the process heater. Process heater requirements for the vacuum distillation column are approximately 245 megajoules per cubic meter (MJ/m³) (37,000 British thermal units per barrel [Btu/bbl]) of topped crude processed in the vacuum column. Process heater emissions and their control are discussed below. Fugitive hydrocarbon emissions from leaking seals and fittings are also associated with the vacuum distillation unit, but these are minimized by the low operating pressures and low vapor pressures in the unit. Fugitive emission sources are also discussed later.

Control technology applicable to the noncondensable emissions vented from the vacuum ejectors or pumps includes venting into blowdown systems or fuel gas systems, and incineration in furnaces or

waste heat boilers.^{2,12-13} These control techniques are generally greater than 99 percent efficient in the control of hydrocarbon emissions, but they also contribute to the emission of combustion products.

5.1.2.2 Catalytic Cracking -

~~Catalytic cracking, using~~Using heat, pressure, and catalysts, ~~catalytic cracking~~ converts heavy oils into lighter products with product distributions favoring the more valuable gasoline and distillate blending components. Feedstocks are usually gas oils from atmospheric distillation, vacuum distillation, coking, and deasphalting processes. These feedstocks typically have a boiling range of 340 to 540°F (650 to 1000°F). All of the catalytic cracking processes in use today can be classified as either fluidized-bed or moving-bed units.

5.1.2.2.1 Fluidized-bed Catalytic Cracking (FCC) -

The FCC process uses a catalyst in the form of very fine particles that act as a fluid when aerated with a vapor. Fresh feed is preheated in a process heater and introduced into the bottom of a vertical transfer line or riser with hot regenerated catalyst. The hot catalyst vaporizes the feed, bringing both to the desired reaction temperature, 470 to 525°C (880 to 980°F). The high activity of modern catalysts causes most of the cracking reactions to take place in the riser as the catalyst and oil mixture flows upward into the reactor. The hydrocarbon vapors are separated from the catalyst particles by cyclones in the reactor. The reaction products are sent to a fractionator for separation.

The spent catalyst falls to the bottom of the reactor and is steam stripped as it exits the reactor bottom to remove absorbed hydrocarbons. The spent catalyst is then conveyed to a regenerator. In the regenerator, coke deposited on the catalyst as a result of the cracking reactions is burned off in a controlled combustion process with preheated air. Regenerator temperature is usually 590 to 675°C (1100 to 1250°F). The catalyst is then recycled to be mixed with fresh hydrocarbon feed.

5.1.2.2.2 Moving-bed Catalytic Cracking-

In the moving-bed system, typified by the Thermafor Catalytic Cracking (TCC) units, catalyst beads (~0.5 centimeters [cm] [0.2 inches (in.)]) flow into the top of the reactor, where they contact a mixed-phase hydrocarbon feed. Cracking reactions take place as the catalyst and hydrocarbons move concurrently downward through the reactor to a zone where the catalyst is separated from the vapors. The gaseous reaction products flow out of the reactor to the fractionation section of the unit. The catalyst is steam stripped to remove any adsorbed hydrocarbons. It then falls into the regenerator, where coke is burned from the catalyst with air. The regenerated catalyst is separated from the flue gases and recycled to be mixed with fresh hydrocarbon feed. The operating temperatures of the reactor and regenerator in the TCC process are comparable to those in the FCC process.

Air emissions from catalytic cracking processes are (1) combustion products from process heaters and (2) flue gas from catalyst regeneration. Emissions from process heaters are discussed below. Emissions from the catalyst regenerator include hydrocarbons, oxides of sulfur, ammonia, aldehydes, oxides of nitrogen, cyanides, (Table 5.1-2), carbon monoxide (CO), and particulates (Table 5.1-1). The particulate emissions from FCC units are much greater than those from TCC units because of the higher catalyst circulation rates used.^{2-3,5}

FCC particulate emissions are controlled by cyclones and/or electrostatic precipitators- or wet scrubbers. Particulate control efficiencies are as high as 80 to 85 percent.^{3,5} Carbon monoxide waste heat boilers reduce the CO and hydrocarbon emissions from FCC units to negligible levels.³ TCC catalyst regeneration produces similar pollutants to FCC units, but in much smaller quantities (Table 5.1-1). The particulate emissions from a TCC unit are normally controlled by high-efficiency cyclones. Carbon monoxide and hydrocarbon emissions from a TCC unit are incinerated to negligible levels by passing the

flue gases through a process heater firebox or smoke plume burner. In some installations, sulfur oxides are removed by passing the regenerator flue gases through a water or caustic scrubber.^{2-3,5}

5.1.2.3 Thermal Cracking -

Thermal cracking processes include visbreaking and coking, which break heavy oil molecules by exposing them to high temperatures.

5.1.2.3.1 Visbreaking -

Topped crude or vacuum residuals are heated and thermally cracked (455 to 480°C, 3.5 to 17.6 kg/cm² [850 to 900°F, 50 to 250 pounds per square inch gauge (psig)]) in the visbreaker furnace to reduce the viscosity, or pour point, of the charge. The cracked products are quenched with gas oil and flashed into a fractionator. The vapor overhead from the fractionator is separated into light distillate products. A heavy distillate recovered from the fractionator liquid can be used as either a fuel oil blending component or catalytic cracking feed.

5.1.2.3.2 Coking -

Coking is a thermal cracking process used to convert low value residual fuel oil to higher-value gas oil and petroleum coke. Vacuum residuals and thermal tars are cracked in the coking process at high temperature and low pressure. Products are petroleum coke, gas oils, and lighter petroleum stocks. Delayed coking is the most widely used process today, ~~but fluid coking is expected to become an important process in the future.~~

In the delayed coking process, heated charge stock is fed into the bottom of a fractionator, where light ends are stripped from the feed. The stripped feed is then combined with recycle products from the coke drum and rapidly heated in the coking heater to a temperature of 480 to 590°C (900 to 1100°F). Steam injection is used to control the residence time in the heater. The vapor-liquid feed leaves the heater, passing to a coke drum where, with controlled residence time, pressure (1.8 to 2.1 kg/cm² [25 to 30 psig]), and temperature (400°C [750°F]), it is cracked to form coke and vapors. Vapors from the drum return to the fractionator, where the thermal cracking products are recovered. Unlike most other refinery operations that are continuous, the delayed coking process is operated in a semi-batch system. A typical delayed coking unit will have one or more coke drums, with at least one coke drum receiving feed at any one time. When the processing coke drum becomes filled with coke, the feed is diverted to a second coke drum. The full coke drum is purged and cooled by adding steam, and later water, to the vessel. After the coke drum is sufficiently cooled, the drum is opened, the water drained, and the coke is removed from the vessel using high pressure water. After the coke is cut out of the drum, the drum is closed and prepared to go back on-line. A typical coke drum cycle is 28 to 36 hours from start of feed to start of next feed to the same coke drum.

In the fluid coking process, typified by FlexicokingTM, residual oil feeds are injected into the reactor, where they are thermally cracked, yielding coke and a wide range of vapor products. Vapors leave the reactor and are quenched in a scrubber, where entrained coke fines are removed. The vapors are then fractionated. Coke from the reactor enters a heater and is devolatilized. The volatiles from the heater are treated for fines and sulfur removal to yield a particulate-free, low-sulfur fuel gas. The devolatilized coke is circulated from the heater to a gasifier where 95 percent of the reactor coke is gasified at high temperature with steam and air or oxygen. The gaseous products and coke from the gasifier are returned to the heater to supply heat for the devolatilization. These gases exit the heater with the heater volatiles through the same fines and sulfur removal processes.

~~From available literature, it is unclear what emissions are released and where they are released.~~
Air emissions from thermal cracking processes include coke dust from decoking operations,

combustion gases from the visbreaking and coking process heaters, and fugitive emissions. Emissions from the process heaters are discussed below. Fugitive emissions from miscellaneous leaks are significant because of the high temperatures involved, and are dependent upon equipment type and configuration, operating conditions, and general maintenance practices. Fugitive emissions are also discussed below. Particulate emissions from ~~delayed~~ coking operations are potentially very significant. These emissions are associated with removing the coke from the coke drum (coke cutting operations in delayed coking units) and ~~subsequent~~ coke handling and storage operations. Particulate emission control is accomplished in coke handling operations by wetting down the coke.⁵ Hydrocarbon emissions are also associated with cooling and venting the coke drum before coke removal. ~~However, comprehensive data for delayed coking emissions have not been included in available literature.~~⁴⁻⁵ Generally, emissions during the initial cooling process are collected in an enclosed system and routed to the refinery gas plant or flare.⁴⁻⁵ Near the end of the cooling cycle, the emissions are vented to the atmosphere. Methods for estimating the emissions during this venting and subsequent decoking steps are presented in the *Emission Estimation Protocol for Petroleum Refineries*.¹⁸

~~Particulate emission control is accomplished in the decoking operation by wetting down the coke.⁵ Generally, there is no control of hydrocarbon emissions from delayed coking. However, some facilities are now collecting coke drum emissions in an enclosed system and routing them to a refinery flare.⁴⁻⁵~~

5.1.2.4 Utilities Plant -

The utilities plant supplies the steam necessary for the refinery. Although the steam can be used to produce electricity by throttling through a turbine, it is primarily used for heating and separating hydrocarbon streams. When used for heating, the steam usually heats the petroleum indirectly in heat exchangers and returns to the boiler. In direct contact operations, the steam can serve as a stripping medium or a process fluid. Steam may also be used in vacuum ejectors to produce a vacuum. Boiler emissions and applicable emission control technology are discussed in much greater detail in Chapter 1.

5.1.2.5 Catalytic Reforming Unit -

The catalytic reforming process involves a complicated series of reactions that occur over a catalyst that change the chemical structure of the hydrocarbons to produce a high-octane gasoline blending stock. The predominant reaction is the dehydrogenation of naphthenes to form aromatics. The reactions occur over a noble metal catalyst, such as platinum or rhenium. The feedstocks for reforming (referred to as naphtha) are first treated to remove sulfur and other compounds that would poison the reforming catalyst. Because the reforming reaction is endothermic, heat must be continually supplied to the system to maintain optimal reaction temperatures. This is typically accomplished by performing the reaction in a series of reactors and applying heat to the naphtha/product stream through heat exchangers between each reactor.

The reforming products are separated into a gas and a liquid stream. The gas stream, which is comprised primarily of hydrogen released as a byproduct of the dehydrogenation reactions, is compressed for use in other refinery processes, with a portion of the gas stream going back to the reformer. The liquid hydrocarbon stream is sent to a fractionation column for final product separation. There are no direct atmospheric vents from the naphtha-reforming process. As the reaction progresses, coke deposits accumulate on the catalyst particles and reduce their reactivity. Consequently, the catalyst must be occasionally regenerated.

There are three basic types of CRU catalyst regeneration operations: continuous, cyclic, and semi-regenerative. Continuous CRU catalyst regenerators operate continuously with a small slip stream of catalyst being re-circulated between the CRU and the regenerator. In a cyclic CRU, there is essentially an extra CRU reactor. When regeneration is needed, one reactor is cycled offline and regenerated. The regeneration of the offline reactor is a batch process. When complete, the reactor is returned to service, and the next reactor is cycled offline and regenerated. This process continues until all reactors are regenerated. In a cyclic CRU, regeneration may occur for 1,000 to 4,000 hours per year. The semi-regenerative CRU operates without regeneration for 8 to 18 months, and then the entire unit is brought offline and regenerated. The overall regeneration cycle typically takes 1 to 2 weeks.

During regeneration, there are several potential atmospheric vents. Although the location of the emission points might vary depending on whether catalyst regeneration is continuous, cyclic, or semi-regenerative, there are three times or locations during the regeneration process that emissions can occur regardless of the regenerator type. For continuous regeneration, venting occurs from three distinct vents as follows: (1) the initial depressurization and purge vent; (2) the coke burn pressure control vent; and (3) the final catalyst purge vent. For cyclic and semi-regenerative units, the initial depressurization and purge vent is often a distinct release point, but the coke burn and final catalyst purge emissions are commonly released at different times during the regeneration cycle from a single atmospheric vent.

The initial depressurization and purge cycle removes the hydrocarbons from the catalyst prior to CRU catalyst regeneration. The gases generated from the initial depressurization and purge cycles are typically vented to the refinery fuel gas system or directly to a combustion device (e.g., flare or process heater). The coke burn cycle is typically the largest (in terms of gas volume) emissions source of the overall catalyst regeneration cycle. The final purge and reduction cycle removes O₂ and any remaining chlorination agent from the system and reduces the catalyst prior to returning the CRU catalyst to the reforming process or bringing the unit back online. The final purge gases are typically vented into the atmosphere or to the refinery fuel gas system depending on the O₂ content of the purge gases (safety considerations restrict the venting of O₂-containing gases to the refinery fuel gas system).

5.1.2.6 Hydrogen Plant -

Steam methane reforming (SMR) is the primary means by which hydrogen (H₂) is produced at a petroleum refinery. Catalytic reforming units also contribute to the hydrogen production totals at a refinery, but the quantity of hydrogen produced as a byproduct in the CRU is generally not adequate to meet the hydrogen needs at the refinery. The catalytic reforming process is described in Section 5.1.2.5. This section focuses on processes designed specifically to produce hydrogen.

Refinery fuel gas and methane are typically used as the feedstocks to the H₂ plant. The feedstock is combined with steam in a series of reactors at high temperatures (750°C to 800°C) to produce a mixture of H₂ and CO. The SMR reaction is endothermic, meaning the reaction requires heat in order to proceed. Therefore, additional natural gas (i.e., natural gas in addition to that used to produce hydrogen) must be supplied to the SMR furnace to provide the necessary heat for the SMR reaction. A water-gas shift (WGS) reaction is then conducted in a separate series of catalytic reactors to convert the CO and steam to CO₂ and H₂.

There are different methods used to separate H₂ from the CO₂ in the SMR-WGS product stream: the most common methods are amine absorption, pressure-swing adsorption (PSA), and membrane separation. In a typical hydrogen production process with PSA or membrane purification, high CO₂ "tail gas" is directed to the SMR furnace for combustion of organic impurities. For these hydrogen production units, the flue gas from the SMR furnace contains both the process tail gas emissions and combustion emissions from the SMR furnace. For other hydrogen production plants, particularly those that use amine adsorption, the process CO₂ stream recovered from the purification step is not returned to the SMR furnace. In this configuration, there are two separate emission stacks: the absorber (or purification system) off-gas, which is nearly pure CO₂, and the SMR process heater flue gas. Several H₂ plants with this design capture the process CO₂ (absorber off-gas) for sale as a by-product.

The various H₂ plant vents typically contain low levels of hydrocarbons. The PSA off-gas vent contains hydrocarbons and methanol. Condensed water from the water-gas shift reactors is often returned to the boiler feed water system after stripping or deaerating the CO₂ from the water; the deaerator vent contains methanol and hydrocarbons. These PSA off-gas vent and deaerator vent may be directed to the steam methane reforming furnace, which is expected to reduce the hydrocarbon emissions. The steam methane reforming furnace vent may contain CO, NO_x, and low levels of hydrocarbons.

5.1.2.7 Sulfur Recovery Plant -

Sulfur recovery plants are used in petroleum refineries to convert the hydrogen sulfide (H₂S) separated from refinery gas streams into the more disposable byproduct, elemental sulfur. Emissions from sulfur recovery plants and their control are discussed in Section 8.13, "Sulfur Recovery".

5.1.2.68 Blowdown System -

The blowdown system provides for the safe disposal of hydrocarbons (vapor and liquid) discharged from pressure relief devices.

Most refining processing units and equipment subject to planned or unplanned hydrocarbon discharges are manifolded into a collection unit, called blowdown system. By using a series of flash drums and condensers arranged in decreasing pressure, blowdown material is separated into vapor and liquid cuts. The separated liquid is recycled into the refinery. The gaseous cuts can either be smokelessly flared or recycled.

Uncontrolled blowdown emissions primarily consist of hydrocarbons but can also include any of the other criteria pollutants. The emission rate in a blowdown system is a function of the amount of equipment manifolded into the system, the frequency of equipment discharges, and the blowdown system controls.

Emissions from the blowdown system can be effectively controlled by combustion of the noncondensables in a flare. To obtain complete combustion or smokeless burning (as required by most states), steam is injected in the combustion zone of the flare to provide turbulence and air. Steam injection also reduces emissions of nitrogen oxides by lowering the flame temperature. Controlled emissions are listed in Table 5.1-1.^{2,11}

5.1.2.79 Process Heaters -

Process heaters (furnaces) are used extensively in refineries to supply the heat necessary to raise the temperature of feed materials to reaction or distillation level. They are designed to raise petroleum fluid temperatures to a maximum of about 510°C (950°F). The fuel burned may be refinery gas, natural gas, residual fuel oils, or combinations, depending on economics, operating conditions, and emission requirements. Process heaters may also use CO-rich regenerator flue gas as fuel.

All the criteria pollutants are emitted from process heaters. The quantity of these emissions is a function of the type of fuel burned, the nature of the contaminants in the fuel, and the heat duty of the furnace. Sulfur oxides can be controlled by fuel desulfurization or flue gas treatment. Carbon monoxide and hydrocarbons can be controlled by more combustion efficiency. Currently, 4 general techniques or modifications for the control of nitrogen oxides are being investigated: combustion modification, fuel modification, furnace design, and flue gas treatment. Several of these techniques are being applied to large utility boilers, but their applicability to process heaters has not been established.^{2,14}

5.1.2.810 Compressor Engines -

Many older refineries run high-pressure compressors with reciprocating and gas turbine engines fired with natural gas. Natural gas has usually been a cheap, abundant source of energy. Examples of refining units operating at high pressure include hydrodesulfurization, isomerization, reforming, and hydrocracking. Internal combustion engines are less reliable and harder to maintain than are steam engines or electric motors. For this reason, and because of increasing natural gas costs, very few such units have been installed in the last few years.

The major source of emissions from compressor engines is combustion products in the exhaust gas. These emissions include CO, hydrocarbons, nitrogen oxides, aldehydes, and ammonia. Sulfur oxides may also be present, depending on the sulfur content of the natural gas. All these emissions are significantly higher in exhaust from reciprocating engines than from turbine engines.

The major emission control technique applied to compressor engines is carburetion adjustment similar to that applied on automobiles. Catalyst systems similar to those of automobiles may also be effective in reducing emissions, but their use has not been reported.

5.1.2.911 Sweetening -

Sweetening of distillates is accomplished by the conversion of mercaptans to alkyl disulfides in the presence of a catalyst. Conversion may be followed by an extraction step for removal of the alkyl disulfides. In the conversion process, sulfur is added to the sour distillate with a small amount of caustic and air. The mixture is then passed upward through a fixed-bed catalyst, counter to a flow of caustic entering at the top of the vessel. In the conversion and extraction process, the sour distillate is washed with caustic and then is contacted in the extractor with a solution of catalyst and caustic. The extracted distillate is then contacted with air to convert mercaptans to disulfides. After oxidation, the distillate is settled, inhibitors are added, and the distillate is sent to storage. Regeneration is accomplished by mixing caustic from the bottom of the extractor with air and then separating the disulfides and excess air.

The major emission problem is hydrocarbons from contact of the distillate product and air in the "air blowing" step. These emissions are related to equipment type and configuration, as well as to operating conditions and maintenance practices.⁴

5.1.2.1012 Asphalt Blowing -

The asphalt blowing process polymerizes asphaltic residual oils by oxidation, increasing their melting temperature and hardness to achieve an increased resistance to weathering. The oils, containing a large quantity of polycyclic aromatic compounds (asphaltic oils), are oxidized by blowing heated air through a heated batch mixture or, in a continuous process, by passing hot air countercurrent to the oil flow. The reaction is exothermic, and quench steam is sometimes needed for temperature control. In some cases, ferric chloride or phosphorus pentoxide is used as a catalyst to increase the reaction rate and to impart special characteristics to the asphalt.

Air emissions from asphalt blowing are primarily hydrocarbon vapors vented with the blowing air. The quantities of emissions are small because of the prior removal of volatile hydrocarbons in the distillation units, but the emissions may contain hazardous polynuclear organics. Emissions are 30 kg/megagram (Mg) (60 lb/ton) of asphalt.¹³ Emissions from asphalt blowing can be controlled to negligible levels by vapor scrubbing, incineration, or both.^{4,13}

5.1.3 Fugitive Emissions And Controls

Fugitive emission sources include leaks of hydrocarbon vapors from process equipment and evaporation of hydrocarbons from open areas, rather than through a stack or vent. Fugitive emission sources include valves of all types, flanges, pump and compressor seals, process drains, cooling towers, and oil/water separators. Fugitive emissions are attributable to the evaporation of leaked or spilled petroleum liquids and gases. Normally, control of fugitive emissions involves minimizing leaks and spills through equipment changes, procedure changes, and improved monitoring, housekeeping, and maintenance practices. Controlled and uncontrolled fugitive emission factors for the following sources are listed in Table 5.1-2:

- Oil/water separators (waste water treatment)
- Storage
- Transfer operations
- Cooling towers

Emission factors for fugitive leaks from the following types of process equipment can be found in *Protocol For Equipment Leak Emission Estimates*, EPA-453/R-93-026, June 1993, or subsequent updates:

- Valves (pipeline, open ended, vessel relief)
- Flanges
- Seals (pump, compressor)
- Process drains

Table 5.1-2 (Metric And English Units). FUGITIVE EMISSION FACTORS
FOR PETROLEUM REFINERIES^a

EMISSION FACTOR RATING: D

<u>Emission Source</u>	<u>Emission Factor Units</u>	<u>Emission Factors</u>		<u>Applicable Control Technology</u>
		<u>Uncontrolled Emissions</u>	<u>Controlled Emissions</u>	
<u>Cooling towers^b</u>	<u>kg/10⁶ L cooling water</u>	<u>0.7</u>	<u>0.08</u>	<u>Minimization of hydrocarbon leaks into cooling water system; monitoring of cooling water for hydrocarbons</u>
	<u>lb/10⁶ gal cooling water</u>	<u>6</u>	<u>0.7</u>	<u>Minimization of hydrocarbon leaks into cooling water system; monitoring of cooling water for</u>

<u>Emission Source</u>	<u>Emission Factor Units</u>	<u>Emission Factors</u>		<u>Applicable Control Technology</u>
		<u>Uncontrolled Emissions</u>	<u>Controlled Emissions</u>	
<u>Oil/water separators^c</u>	<u>kg/10³ L waste water</u>	<u>0.6</u>	<u>0.024</u>	<u>hydrocarbons</u> <u>Covered separators and/or vapor recovery systems</u>
	<u>lb/10³ gal waste water</u>	<u>5</u>	<u>0.2</u>	<u>Covered separators and/or vapor recovery systems</u>
<u>Storage</u>	<u>See Chapter 7 - Liquid Storage Tanks</u>			
<u>Loading</u>	<u>See Section 5.2 - Transportation And Marketing Of Petroleum Liquids</u>			

^a References 2,4,12-13.

^b If cooling water rate is unknown (in liters or gallons) assume it is 40 times the refinery feed rate (in liters or gallons). Refinery feed rate is defined as the crude oil feed rate to the atmospheric distillation column. 1 bbl (oil) = 42 gallons (gal), 1 m³ = 1000 L.

^c If waste water flow rate to oil/water separators is unknown (in liters or gallons) assume it is 0.95 times the refinery feed rate (in liters or gallons). Refinery feed rate is defined as the crude oil feed rate to the atmospheric distillation column. 1 bbl (oil) = 42 gal, 1 m³ = 1000 L.

5.1.3.1 Valves, Flanges, Seals, And Drains -

For these sources, a very high correlation has been found between mass emission rates and the type of stream service in which the sources are employed. The four stream service types are (1) hydrocarbon gas/vapor streams (including gas streams with up to 50 percent hydrogen by volume), (2) light liquid and gas/liquid streams, (3) kerosene and heavier liquid streams (includes all crude oils), and (4) gas streams containing more than 50 percent hydrogen by volume. It is found that sources in gas/vapor stream service have higher emission rates than those in heavier stream service. This trend is especially pronounced for valves and pump seals. The size of valves, flanges, pump seals, compressor seals, relief valves, and process drains does not affect their leak rates.¹⁷ The emission factors are independent of process unit or refinery throughput.

Valves, because of their number and relatively high emission factor, are the major emission source. This conclusion is based on an analysis of a hypothetical refinery coupled with the emission rates. The total quantity of fugitive VOC emissions in a typical oil refinery with a capacity of 52,500 m³ (330,000 bbl) per day is estimated as 20,500 kg (45,000 lb) per day (see Table 5.1-3). This estimate is based on a typical late 1970s refinery without a leak inspection and maintenance (I/M) program. See the *Protocol* document for details on how to estimate emissions for a specific refinery.

~~Table 5.1-2 (Metric And English Units). FUGITIVE EMISSION FACTORS
FOR PETROLEUM REFINERIES*~~

~~EMISSION FACTOR RATING: D~~

Emission Source	Emission Factor Units	Emission Factors		Applicable Control Technology
		Uncontrolled Emissions	Controlled Emissions	
Cooling towers^b	kg/10⁶ L cooling water	0.7	0.08	Minimization of hydrocarbon leaks into cooling water system; monitoring of cooling water for hydrocarbons
	lb/10⁶ gal cooling water	6	0.7	Minimization of hydrocarbon leaks into cooling water system; monitoring of cooling water for hydrocarbons
Oil/water separators^c	kg/10³ L waste water	0.6	0.024	Covered separators and/or vapor recovery systems
	lb/10³ gal waste water	5	0.2	Covered separators and/or vapor recovery systems
Storage	See Chapter 7 - Liquid Storage Tanks			
Loading	See Section 5.2 - Transportation And Marketing Of Petroleum Liquids			

^a~~References 2,4,12-13.~~

^b~~If cooling water rate is unknown (in liters or gallons) assume it is 40 times the refinery feed rate (in liters or gallons). Refinery feed rate is defined as the crude oil feed rate to the atmospheric distillation column. 1 bbl (oil) = 42 gallons (gal), 1 m³ = 1000 L.~~

^c~~If waste water flow rate to oil/water separators is unknown (in liters or gallons) assume it is 0.95 times the refinery feed rate (in liters or gallons). Refinery feed rate is defined as the crude oil feed rate to the atmospheric distillation column. 1 bbl (oil) = 42 gal, 1 m³ = 1000 L.~~

5.1.3.2 Storage -

All refineries have a feedstock and product storage area, termed a "tank farm", which provides surge storage capacity to ensure smooth, uninterrupted refinery operations. Individual storage tank capacities range from less than 160 m³ to more than 79,500 m³ (1,000 to 500,000 bbl). Storage tank designs, emissions, and emission control technology are discussed in detail in AP-42 Chapter 7, and the TANKS software program is available to perform the emissions calculations, if desired.

Table 5.1-3 (Metric And English Units). FUGITIVE VOC EMISSIONS FROM AN UNCONTROLLED OIL REFINERY OF 52,500 m³/day (330,000 bbl/day) CAPACITY ^a

Source	Number	VOC Emissions	
		kg/day	lb/day
Valves	11,500	3,100	6,800
Flanges	46,500	300	600
Pump seals	350	590	1,300
Compressor seals	70	500	1,100
Relief valves	100	200	500
Drains	650	450	1,000
Cooling towers ^b	1	730	1,600
Oil/water separators (uncovered) ^b	1	14,600	32,100
TOTAL	C	20,500	45,000

^a Reference 17.

^b Based on limited data.

5.1.3.3 Transfer Operations -

Although most refinery feedstocks and products are transported by pipeline, some are transported by trucks, rail cars, and marine vessels. They are transferred to and from these transport vehicles in the refinery tank farm area by specialized pumps and piping systems. The emissions from transfer operations and applicable emission control technology are discussed in much greater detail in Section 5.2, "Transportation And Marketing Of Petroleum Liquids".

5.1.3.4 Waste Water Treatment Plant -

All refineries employ some form of waste water treatment so water effluents can safely be returned to the environment or reused in the refinery. The design of waste water treatment plants is complicated by the diversity of refinery pollutants, including oil, phenols, sulfides, dissolved solids, and toxic chemicals. Although the treatment processes employed by refineries vary greatly, they generally include neutralizers, oil/water separators, settling chambers, clarifiers, dissolved air flotation systems, coagulators, aerated lagoons, and activated sludge ponds. Refinery water effluents are collected from various processing units and are conveyed through sewers and ditches to the treatment plant. Most of the treatment occurs in open ponds and tanks.

The main components of atmospheric emissions from waste water treatment plants are fugitive VOCs and dissolved gases that evaporate from the surfaces of waste water residing in open process drains, separators, and ponds (Table 5.1-2). Treatment processes that involve extensive contact of waste water and air, such as aeration ponds and dissolved air flotation, have an even greater potential for atmospheric emissions. Section 4.3, "Waste Water Collection, Treatment And Storage", discusses estimation techniques for such water treatment operations. ~~WATER8 and SIMS software models are available to perform the calculations.~~

The control of waste water treatment plant emissions involves covering systems where emission generation is greatest (such as oil/water separators and settling basins) and removing dissolved gases from water streams with sour water strippers and phenol recovery units before their contact with the atmosphere. These control techniques potentially can achieve greater than 90 percent reduction of waste water system emissions.¹³

5.1.3.5 Cooling Towers -

Cooling towers are used extensively in refinery cooling water systems to transfer waste heat from the cooling water to the atmosphere. The only refineries not employing cooling towers are those with once-through cooling. The increasing scarcity of a large water supply required for once-through cooling is contributing to the disappearance of that form of refinery cooling. In the cooling tower, warm cooling water returning from refinery processes is contacted with air by cascading through packing. Cooling water circulation rates for refineries commonly range from 7 to 70 L/minute per m³/day (0.3 to 3.0 gal/minute per bbl/day) of refinery capacity.^{2,16}

Atmospheric emissions from the cooling tower consist of fugitive VOCs and gases stripped from the cooling water as the air and water come into contact. These contaminants enter the cooling water system from leaking heat exchangers and condensers. Although the predominant contaminants in cooling water are VOCs, dissolved gases such as H₂S and ammonia may also be found (see Table 5.1-2).^{2,4,17}

Control of cooling tower emissions is accomplished by reducing contamination of cooling water through the proper maintenance of heat exchangers and condensers. The effectiveness of cooling tower controls is highly variable, depending on refinery configuration and existing maintenance practices.⁴

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